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Published in:
Proceedings of Nonlinear Optics: Materials, Fundamentals and Applications (NLO)

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Steffensen, H., Rottwitt, K., Jepsen, P. U., & Bang, O. (2011). Influence of Two Photon Absorption on Soliton Self-Frequency Shift. In *Proceedings of Nonlinear Optics: Materials, Fundamentals and Applications (NLO)* (pp. NWE16)

Influence of Two Photon Absorption on Soliton Self-Frequency Shift

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Abstract: The creation of mid-infrared supercontinua necessitates the use of soft-glass fibers. However, some materials, like chalcogenide, have a substantial two photon absorption. We introduce a model for soliton self-frequency shift that successfully includes this effect.

OCIS codes: 060.4370, 060.5530.

1. Introduction

The fundamentals in achieving a wide supercontinuum spectrum is strong pumping in an optical fiber close to the zero dispersion point to create soliton fission, which allows for fundamental solitons to self-frequency shifting to form the red edge of the spectrum, while group velocity matched dispersive waves blue shift to form the blue edge [1]. Due to the loss edge of silica, it is not possible to extend the supercontinuum into the mid-infrared. Instead there is an increasing interest in using soft-glass fibers such as chalcogenide [2, 3] for mid-infrared supercontinuum generation (SCG). However in chalcogenide as an example, there is a high level of two photon absorption (TPA) [4], which causes a reduction of peak power and thus leads to a reduced soliton self-frequency shift (SSFS). Existing models [5–7] do not account for this, so we derive a new model which for the first time accounts for the influence of TPA on the SSFS.

2. Model

The model is based on the generalized nonlinear Schrödinger equation (GNLS), as given by

$$\partial_z u(z,t) + \frac{\alpha}{2} u(z,t) - i \sum_{m\geq 2} \frac{i^m \beta_m}{m!} \partial_t^m u(z,t) = i \sum_{n\geq 0} \frac{i^n \gamma_n}{n!} \partial_t^n \left[u(z,t) \int R(t') |u(z,t-t')|^2 \mathrm{d}t' \right], \tag{1}$$

where u is the complex field envelope at carrier frequency ω_0, α is linear loss, β_m and γ_m are the m'th derivative at ω_0 of the group velocity dispersion (GVD) and the nonlinear coefficient, respectively, and finally $R(t)$ is the time response given by $R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$, which includes both the instantaneous Kerr and delayed Raman response, given as $h_R(t)$. The nonlinear coefficient, when TPA is present, is given by [8]

$$\gamma = \frac{2\pi n_2}{\omega A_{\mathrm{eff}}} + \frac{i\beta_{\mathrm{TPA}}}{2A_{\mathrm{eff}}}, \tag{2}$$

where n_2 is the nonlinear refractive index, c is the speed of light, β_{TPA} is the TPA coefficient and A_{eff} is the effective area. Only the first two elements of each sum have been included. The model is based on the soliton ansatz

$$u(z,t) = \sqrt{P_0(z)} \mathrm{sech}\left(\frac{t - t_c(z)}{T_0(z)} \right) \exp\left[i\Phi(z) - ib(z)(t - t_c(z)) - i\mu(z)(t - t_c(z))^2 \right], \tag{3}$$

with b, t_c, T_0, P_0, μ being the frequency shift, pulse center, width, peak power, and quadratic chirp, respectively. With this ansatz and the method of moments, based on the evolution of five moments, it is possible to derive a set of differential equation for the soliton parameters b, t_c, T_0, P_0, μ [6,7]. In a moving frame of reference and for long pulses, the equations reduce to

$$\frac{db}{dz} \approx -\frac{8}{15}\frac{\gamma_0^r P_0 T_R}{T_0^2} + \frac{4}{3}\mu\gamma_1^r P_0 - \frac{4}{3}\mu\gamma_0^i P_0 T_R - \frac{4}{5}\frac{\gamma_1^i P_0}{T_0^2} - 4\left(\frac{\pi^2}{9} - \frac{2}{3}\right)\mu^2\gamma_1^i P_0 T_0^2, \tag{4a}$$

$$\frac{dt_c}{dz} \approx \frac{1}{2}\beta_3\left[\frac{\pi^2}{3}\mu^2 T_0^2 + \frac{1}{3T_0^2}\right] + \gamma_1^r P_0 - \frac{2}{3}\gamma_0^i P_0 T_R - 2\left(\frac{\pi^2}{9} - \frac{2}{3}\right)\mu\gamma_1^i P_0 T_0^2, \tag{4b}$$

$$\frac{dT_0}{dz} \approx 2\mu T_0\beta_2 + \frac{8}{\pi^2}\frac{\gamma_1^r P_0 T_R}{T_0} + \frac{4}{\pi^2}\gamma_0^i P_0 T_0 - \left(\frac{4}{3} - \frac{12}{\pi^2}\right)\mu\gamma_1^i P_0 T_0 T_R, \tag{4c}$$

$$\frac{dP_0}{dz} \approx -\alpha P_0 - 2\mu P_0\beta_2 - \left(\frac{8}{\pi^2} + \frac{8}{15}\right)\frac{\gamma_1^r P_0^2 T_R}{T_0^2} - \left(\frac{4}{3} + \frac{4}{\pi^2}\right)\gamma_0^i P_0^2 - \frac{12}{\pi^2}\mu\gamma_1^i P_0^2 T_R, \tag{4d}$$

$$\frac{d\mu}{dz} \approx \left(\frac{2}{\pi^2}\frac{1}{T_0^4} - 2\mu^2\right)\beta_2 + \frac{2}{\pi^2}\frac{\gamma_0^r P_0}{T_0^2} - \left(\frac{8}{15} - \frac{4}{\pi^2}\right)\frac{\mu\gamma_1^r P_0 T_R}{T_0^2} - \frac{76}{15\pi^2}\frac{\gamma_1^i P_0 T_R}{T_0^4}, \tag{4e}$$

where the superscript on γ_n^r and γ_n^i refer to the real and imaginary part, respectively. The full version of the equations, valid for all pulse widths, are too complicated to include in this summary. By looking only on linear loss and loss directly caused by TPA in Eg. (4d), it is possible to obtain an analytical expression for the TPA loss length,

$$L_{\text{TPA}} = \frac{1}{\alpha}\ln\left[\frac{e + \left(\frac{4}{3} + \frac{4}{\pi^2}\right)\frac{\gamma_0^i P_0}{\alpha}}{1 + \left(\frac{4}{3} + \frac{4}{\pi^2}\right)\frac{\gamma_0^i P_0}{\alpha}}\right] \tag{5}$$

which is defined as the length of propagation after which the power is reduced to 1/e of its original value. After this length of propagation, the power has been reduced to such an extent as to effectively halt red-shifting.

3. SSFS in Chalcogenide Fiber

To demonstrate the effect of TPA, a As_2Se_3 chalcogenide fiber has been used for the simulations. The results of the analytic model has been compared to simulations of the GNLS equation to demonstrate the validity. The parameters are for a realistic fiber used for SCG. From Yeom *et. al.* [2] we have $\alpha \approx 0.5$ dB/m and $\beta_2 = -360$ ps^2/km, $\beta_3 = 3.58$ ps^3/km and $A_{\text{eff}} = 0.4773\ \mu$m^2 at 1550nm. The time response have been approximated as a decaying harmonic oscillator with $\tau_1 = 23$ fs and $\tau_2 = 210$ fs and $f_R = 0.1$ based on Hu *et. al.* [3] and finally we have the nonlinear parameters in Table 1 from Nguyen *et. al.* [4]. The figure of merit (FOM) is defined as FOM $= n_2/(\lambda\beta_{\text{TPA}})$

Table 1. Used values of the nonlinearity and two photon absorption

λ (nm)	n_2 (10^{-18}m^2/W)	FOM
1415	11.0	0.8
1434	14.0	0.9
1456	13.0	1.1
1491	9.9	1.45
1515	8.9	1.8
1554	7.0	1.8

The results in Fig. 1 show that TPA has a clear effect in reducing the red shifting of a soliton, for a soliton with an initial width of 25 fs, the total red shift is reduced from 27 nm to 17 nm predicted by the proposed model and from 30 nm to 17 nm by simulation of the GNLS. The reduction in SSFS is predominantly caused by the reduction in peak power caused by the TPA. It also shows that the model in a qualitative manner shows what occurs in SSFS both with and without including TPA. For the short pulse, a reverse frequency shift is seen to occur around $z = 4$ cm and 13.5 cm, caused by the second term in Eq. (4a) and a combination of a broadening of the pulse, a positive chirp and a relatively large γ_1^r, roughly an order of magnitude higher than the usual approximation of γ_0^r/ω_0. It is an effect that will be further investigated in future work.

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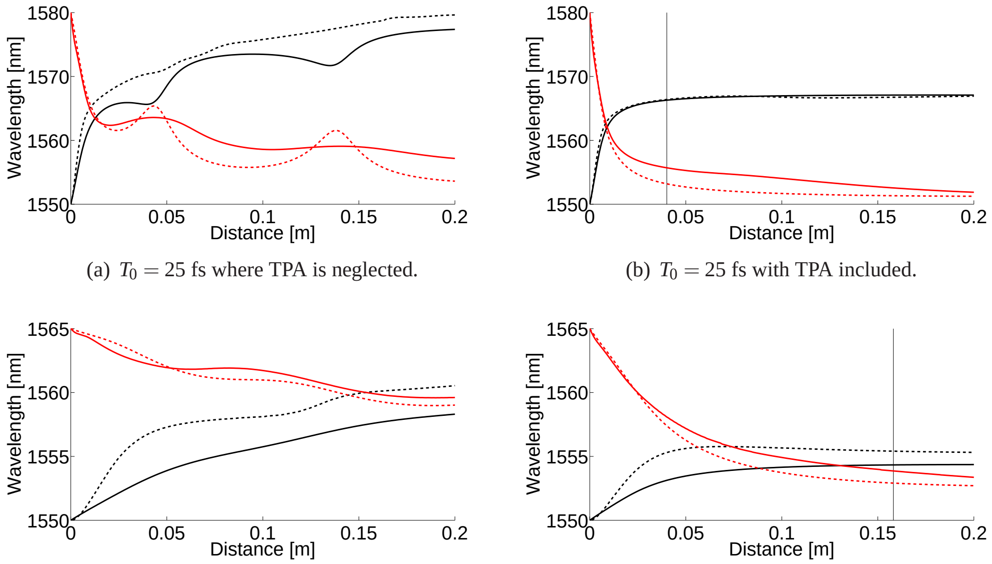

(a) $T_0 = 25$ fs where TPA is neglected.

(b) $T_0 = 25$ fs with TPA included.

(c) $T_0 = 50$ fs where TPA is neglected.

(d) $T_0 = 50$ fs with TPA included.

Fig. 1. Soliton dynamics when neglecting (a), (c) and including (b), (d) TPA for a fundamental soliton with a width of 25 fs (a), (b) and 50 fs (c), (d). The black lines (all originating in the lower left corner) displays the redshift while the red lines (originating in the upper left corner) show the normalized peak power of the soliton. The solid line is obtained with the proposed model while the dashed is from a full simulation of the GNLS. In the two cases where TPA is included, the theoretical TPA loss length have been marked by a vertical line.

4. Conclusion

In summary we have presented a model that successfully account for SSFS under the influence of TPA. Furthermore, it has incorporated the full Raman spectrum and is thus valid for solitons of any width. It accurately depicts the decrease in SSFS caused by TPA in a realistic chalcogenide fiber, specifically for a soliton with a width of 25 fs the total redshift is reduced by 10 nm from 27 nm to 17 nm.

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